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# **INJECTOR-WALL INTERACTIONS IN GAS-CENTERED SWIRL COAXIAL INJECTORS**

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## **ABSTRACT**

Tailored injectors near the wall of a combustion chamber are often an integral part of a rocket engine's thermal management. However, most studies of injectors utilize single, isolated elements. The ability of walls to affect the expansion and stability of single-phase jets has already been well established. The effect of a wall on a multiphase flow, a spray, has not been established. Reported here is the impact a single wall has on the behavior of a spray from a single injector. Of specific interest are parameters which may impact engine performance, specifically attachment length, spray growth and stability. The atomizer being studied is a gas-centered swirl coaxial injector which relies on a dominant gas flow to drive the atomization. High-speed images are analyzed to assess the spray's behavior both qualitatively and quantitatively. Three wall offset ratios, 0.57, 0.83 and 1.16, are compared to the free spray. Sprays are qualitatively similar, but the wall has a quantitative effect on spreading rate. The wall is able to decrease the variability in the spray, but not globally—only very near the wall.

## **INTRODUCTION**

Many rocket engines rely on tailored injectors (wall elements) to provide a more fuel-rich environment near the wall or to help to cool the wall or both. Because these elements operate in a location near the wall, their performance may be different from elements in the center of the injector or from single, separated elements. Due to their importance in protecting the wall of the rocket chamber, it is especially important that the behavior of wall elements is understood. Understanding is particularly important as these injectors are typically tailored in an attempt to provide a specific environment near the wall.

In the past, cold flow tests have been conducted to understand the behavior of many rocket injectors. AFRL has been engaged in studying a specific type of injector, a gas-centered swirl coaxial (GCSC) injector, to understand its operation and develop design guidelines [1]. However, these tests have heretofore been on single, isolated elements operating far from any wall. While this data is useful for understanding the basic physics of the injector's operation, it neglects the important effects of other elements and walls.

The focus of this work is the changes in a spray due to a nearby wall and the interaction of the spray with the wall. A single GCSC injector was studied with three different wall spacings (10 mm, 5 mm and 1 mm from the edge of the outlet) and compared with a free spray (one with no wall nearby). Several different parameters of interest in engine design will be considered including the attachment point, the spread of the spray, the spray's general character and its stability. The wall is shown to alter the spray in important ways which must be considered by designers.

## BACKGROUND

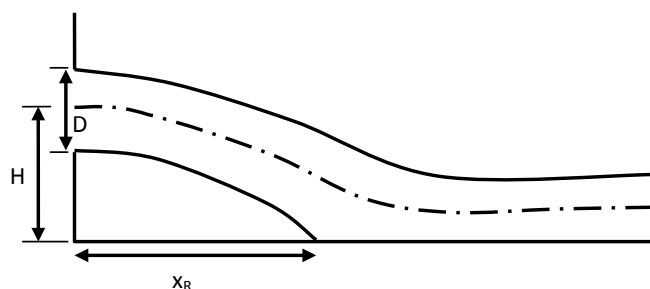
The impact of a wall on the behavior of a single-phase jet has received much attention in the past. However, studies of sprays near and parallel to walls are rare. What literature does exist has been focused on diesel sprays [2]: sprays that lack a strong gas-phase component and, therefore, differ in basic behavior to the sprays produced in GCSC injectors. In general, the scant data for multiphase flows near walls is not applicable to rockets.

Single-phase jets issuing forth near walls are typically called offset-jets. Because they are common in situations such as air conditioning, burners and internal combustion engines they have been studied extensively, especially in the 1960's through 1980's ([3-5], for example). The majority of this work focused on gaseous flows in two-dimensional geometries. Some liquid systems have been studied, particularly in reference to jets near free surfaces, which share some similarities to the classic offset jets [6]. Three-dimensional geometries are more commonly found in these liquid studies where an initially round jet is offset from a planar wall or surface.

Figure 1 shows the basic structure of a single-phase offset jet along with important geometric parameters. The jet resulting from this offset configuration differs in evolution from jets impinging on a wall or the wall-jet configuration (where the jet issues forth immediately next to, i.e. attached to, the wall). An offset jet is initially pulled towards the wall due to the lower pressure zone created close to the jet exit as a result of the partially-confined flow entrainment. At some downstream region, typically called the attachment or reattachment point, the jet attaches to the wall. Here, part of the inner fluid of the jet is directed upstream into the recirculation zone (due to the pressure gradient). The rest of the jet continues downstream eventually developing to resemble wall-jet flow. As would be expected, the initial shape of the jet, e.g. round or planar, has a dramatic impact on the evolution of this flow, especially in the area from reattachment to wall-jet development [4].

Sprays where the droplets are being carried by a moving gas flow would be expected to share some of the characteristic of single-phase offset jets, but they would also be expected to have some unique features. These sprays would still create a low pressure zone near the wall and would be expected to curve towards and attach to the wall. Here, though, liquid will be deposited on the wall at and downstream of the attachment point. Some amount of liquid could be directed upstream from the attachment point due to the recirculation zone. A wetted layer at the wall changes the development of the two-phase jet in comparison with the single-phase jet. This is because the no-slip velocity boundary condition will no longer apply at the wall. Studies comparing jets near walls with jets near free surfaces show that the change in boundary condition can cause a dramatic change in jet behavior and development [2]. Note that the spray will not behave as if it is near a free surface, either, since the wall cannot deflect as a free surface could.

Furthermore, the swirling nature of the liquid in a GCSC injector may introduce additional complexities in behavior. While the gas is initially unswirled, it may pick up tangential velocity due to the swirling of the liquid. Swirling gas flows can develop dynamic behaviors, for example a precessing vortex core (PVC) [7], which can be increased or more likely when the spray is confined [7]. The impact of a single wall, however, remains unclear. Multiphase flows also appear to be more prone to the



**Figure 1.** The height ( $H$ ), jet diameter ( $D$ ) and reattachment length ( $x_R$ ) are important parameters describing offset jet flows.

development of organized dynamic behavior compared to single-phase jets [8]. Because earlier studies [9] have observed regular, dynamic behavior in GCSC injectors, the presence of the wall could impact the stability of the spray.

Here, the main metrics for the effect of the wall on a spray are the point where the spray attaches to the wall, the presence or location of the film produced on the wall's surface, the spreading of the spray and the stability of the spray. The attachment point affects the heat transfer to

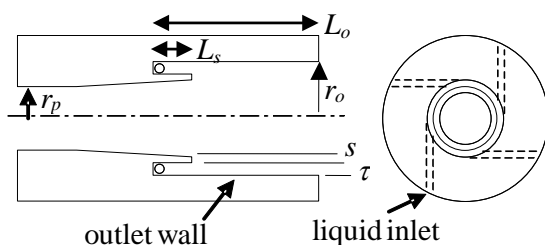
the wall and the cooling potential of the spray. Obviously, in an engine this heat transfer is further complicated by the evaporation and combustion of the liquid which may take place before or after attachment. Knowing the location of the attachment point can indicate whether liquid or possibly the flame front will be impinging on the wall. Liquid is deposited on the wall through attachment, because some droplets possess radial velocity which can move them towards the wall and because droplet-laden flow is trapped near the wall due to the recirculation zone. The film is useful in cooling the wall, but too much film would obviously negatively impact the engine's performance. If the wall changes the spreading of the spray in the directions away from the wall, the mixing between wall elements and main elements would be impacted. Often, the interelement mixing is needed to ensure good performance (but too much mixing could result in a hotter than anticipated environment near the wall). Single-phase studies show that the wall alters the shear layer opposite the wall [10], so alterations in spreading are expected. Finally, the stability of the spray can have a direct impact on the stability of the combustion zone and the engine as a whole.

## EXPERIMENTAL SET-UP

The injector used in this study is illustrated in Fig. 2. Gas enters along a central, 6.35 mm radius post ( $r_p$ ) with an L/D of  $\sim 14$ . The liquid enters through four, tangentially drilled holes each 1.535 mm in diameter. The gas velocity greatly exceeds the liquid velocity, and the resulting shear at the interface strips the liquid film. The range of gas and liquid velocities are given in Table 1 along with the momentum flux ratio which is defined as  $(\rho_l/\rho_g)(v_g/v_l)^2$  where  $\rho$  is the density,  $v$  is the velocity,  $g$  denotes gas,  $l$  denotes liquid. The velocities are the mean gas velocity including compressible effects and the total liquid velocity. The geometric parameters needed to calculate these velocities are given in Fig. 2 [1]. The gas density is calculated including compressibility effects. In all of the cases reported here the liquid film has been completely stripped prior to the injector exit, 35.2 mm downstream of the liquid inlet. The remaining geometric parameters of importance are the radius of the injector's outer cup ( $r_o$ ), 7.62 mm, the liquid film's initial thickness ( $\tau$ ), 1.65 mm, the height of the lip initially separating the gas and liquid ( $s$ ), 1.52 mm, and the length of this separating lip, 3.2 mm. The main injector body is acrylic with the majority of the gas post being stainless steel.

The fluids used in this experiment are gaseous nitrogen and demineralized water. Their flow rates are metered with sonic nozzles and cavitating venturis, respectively. The nozzles, venturis and associated pressure transducers have been calibrated so that the error in mass flow rates is 0.227 g/s. The spray exits into atmospheric pressure air; however, since the experimental facility is well above sea level, the typical atmospheric pressure is 0.90 atm. More details on the set-up without the wall can be found in Schumaker et al. [1].

The wall was attached to the injector body so that its length was parallel to the injector axis. The wall was made of acrylic and waxed to improve its hydrophobic properties. Waxing reduced the pendant droplets on the wall's surface, which interfere with the imaging near the wall, but it did not eliminate them. The wall was 246 mm wide and 304.8 mm long. The joint between the wall and the injector body was sealed using vinyl tape to prevent air entrainment through the seam. There were no side walls or other spray enclosures in the vicinity of the spray. It has been shown that side walls improve the two-dimensionality of planar offset jet flows by preventing outside air entrainment [4], but this step was not



**Figure 2.** In this schematic of the GCSC injector, the gas flow is from left to right while the liquid enters the tangential holes. The injector outlet diameter,  $D$ , is equal to  $2r_o$ .

taken due to the already complex three-dimensionality of the current flow, to enhance viewability and to allow future comparisons to fully enclosed offset sprays. The wall and injector are shown in Fig. 3.

Three different offset distances are considered here and compared to the flow with no wall present. Wall offset distances were 1 mm, 5 mm or 10 mm from the edge of the injector outlet. The offset ratio, that is the ratio of wall offset (from jet axis, as shown in Fig. 1) to injector outlet diameter,  $H/D$ , was 1.16, 0.83 or 0.57. These distances are

Wall Offset Ratio	Liquid Flow Rate (kg/s)	Gas Flow Rate (kg/s)	Mom Flux Ratio	$Re_{Dp}$
$\infty$	0.0362	0.0441	43	$6.0 \times 10^5$
$\infty$	0.0468	0.0448	54	$7.7 \times 10^5$
$\infty$	0.0472	0.0369	80	$7.8 \times 10^5$
$\infty$	0.0723	0.0441	87	$12 \times 10^5$
$\infty$	0.0722	0.0484	109	$13 \times 10^5$
1.16	0.0352	0.0441	41	$5.9 \times 10^5$
1.16	0.0448	0.0448	50	$7.4 \times 10^5$
1.16	0.0458	0.037	74	$7.5 \times 10^5$
1.16	0.0682	0.0441	81	$12 \times 10^5$
0.83	0.0358	0.0441	42	$5.9 \times 10^5$
0.83	0.0467	0.0447	53	$7.7 \times 10^5$
0.83	0.0472	0.0369	80	$7.8 \times 10^5$
0.83	0.0721	0.044	87	$12 \times 10^5$
0.83	0.0725	0.0484	110	$13 \times 10^5$
0.57	0.036	0.0442	42	$6.0 \times 10^5$
0.57	0.0461	0.0447	51	$7.4 \times 10^5$
0.57	0.0477	0.037	81	$7.9 \times 10^5$
0.57	0.0718	0.0444	84	$12 \times 10^5$
0.57	0.0732	0.0488	110	$13 \times 10^5$

**Table 1.** The operating conditions investigated in this study are given here.

considered fully turbulent [3, 10], Reynolds number has little effect on flow parameters such as reattachment length.

The spray produced by the GCSC injector is very optically dense and difficult to penetrate with conventional laser diagnostics. As a result, measurements of droplet size and velocities were not attempted. Instead, high speed shadowgraphy is employed to give statistics on global spray behavior. The images are obtained using a Vision Research Phantom v7.3 camera with a framing rate of 6688 frames per second. Typical images with the various wall distances are given as Fig. 4. The backlighting was provided by a 500 W halogen light. This light uses AC power and, as a result, the background exhibited frequencies in the range of 120 Hz resulting from the variations in the lighting. Luckily, this lighting variation does not affect the results as the measured spray parameters do not exhibit dominant frequencies near this value. Great care was taken to ensure the camera was perpendicular to both the injector outlet plane and the wall.

All of the data were processed using in-house Matlab (R2008b) functions. First, an average background image (taken every morning and just prior to or just after a new round of testing) was subtracted from each frame of video. A simple segmentation process using Otsu's method [11] was employed. Once the image was segregated, the spray boundary location was recorded and the width and centerline were calculated. The initial spray diameter is the diameter measured from the time-averaged boundaries. Average values are taken over 3000 frames (1.16 and 0.83 offset ratios up to 35 mm downstream) or 100 frames (all other). Due to droplets adhering to the injector exit, diameters within ~0.5 to 1.5 mm downstream, depending on the test, were unreliable; diameters were therefore set to be the minimum spray diameter; these minima generally occur within 2 mm of the exit. The spray diameter varies with both operating condition and wall location as a result of slight differences in the initial spread



**Figure 3.** The wall and injector are pictured during a typical test.

quite small compared with those typically found in the literature for single-phase, planar offset jets, but the larger two values are in the vicinity of those seen in round jet studies. The Reynolds numbers of the gas flow prior to liquid contact (based on the gas post diameter— $4m_g/(\pi D_p \mu)$ —given in Table 1) are higher than typically seen in the literature. Many studies report, however, that above a threshold value, typically something in a range which assures that the flow can be

of the spray, the scale factors and other parameters. The Matlab program also performs FFT's of various data such as boundary location as functions of time. Frequency content of the spray was extracted from these results. It should be noted, however, that these results are very susceptible to noise in the raw images and give only a general idea of spray stability.

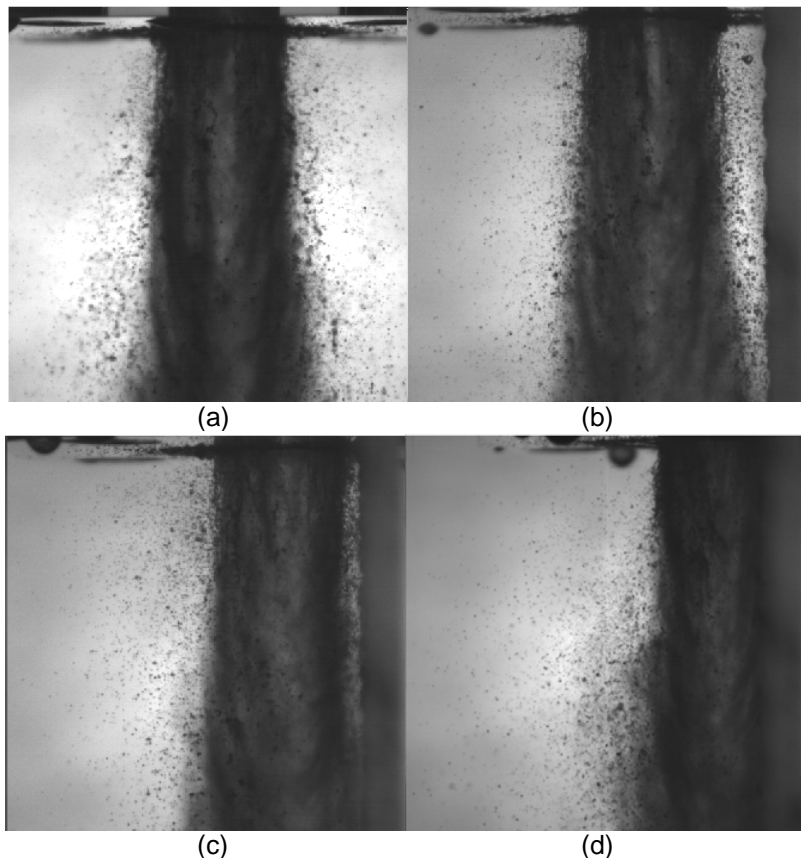
Due to the nature of the data processing and the inherent unsteadiness of the sprays, uncertainties are difficult to determine. An examination of various segregation methods for sprays near the injector outlet suggests that the boundaries can be determined within 2-3 pixels,  $\sim 0.25$  mm, on average. Instantaneous, localized values can differ by 40 pixels ( $\sim 4.5$  mm) or more at some points, but are generally limited to under 10 pixels ( $\sim 1.1$  mm) [12]. Differences vary with lighting, spray density, droplet sizes and scale factors, however. Averaged boundaries are considered here to have uncertainties of  $\pm 0.25$  mm and instantaneous boundaries are considered to have uncertainties of  $\pm 1$  mm; however, these uncertainties should be considered notional and not exact values. The standard deviation could be given as an indication of the uncertainty, but these sprays are not steady and instead the standard deviation largely reflects the real variability within the data. Data was collected down to 90 mm downstream. However, the background illumination was so nonuniform that, even with background subtraction, the uncertainties in boundary location were much larger. However, enough information is available in this range to present some general findings below. It should also be noted that despite difficulties in assessing uncertainty, the image processing results are exactly reproducible regardless of personnel because the data processing is automated.

## RESULTS AND DISCUSSION

### GENERAL SPRAY CHARACTER

Most of the data discussed within this work is from a set of videos near the injector outlet up to 50 mm downstream. An additional set of data was taken from 35 to 90 mm downstream; however, as mentioned above, the lighting only allows some general conclusions to be made.

Over the 90 mm distance of the near-injector dataset the spray opposite the wall is, qualitatively, surprisingly similar across all wall offset ratios. On the wall side, the sprays differ qualitatively only near and downstream of the attachment point. For the 1.16 offset ratio, the spray does not attach to the wall over the 50 mm distance with good lighting; it may attach in a few frames within the 90 mm distance, but the averaged attachment point lies outside of this distance if the spray does remain attached to the wall. Qualitatively, this spray is very similar to the free spray, as



**Figure 4.** Typical images from the highest momentum flux ratio are shown here for the free spray (a), the 1.16 offset ratio wall (b), the 0.83 offset ratio wall (c) and the 0.57 offset ratio wall (d). The field of view in these images extends approximately 50 mm downstream.

shown in Fig. 4. In fact, if the wall is cropped from the picture, it is difficult for an experienced observer to determine which spray is near the wall without making measurements. The “large” droplets and ligaments, which often contain radial velocities, have no obvious trajectory changes due to the wall. Here, “large” indicates the liquid structures which can be distinctly identified as compared to the “small” droplets which appear only as the main shadow part of the shadowgraphy images.

More differences are evident for the case with the 0.83 offset ratio wall. The spray has a noticeable curvature towards the wall. It clearly attaches to the wall at some distance within the 50 mm frame shown in Fig 4. Away from the wall, on the “free side” of the spray, the qualitative differences are small and the spray does not look appreciably different from the free spray. Again, large ligaments and droplets, even those near the wall, do not show a bias due to the presence of the wall. This behavior is not particularly surprising as the large structures are not following the main gas flow, even in the free-spray case. The large size of the structures is a main reason, but their existence on the peripheries of the spray also contributes since the gas velocity in these regions is substantially lower than in the main core of the spray.

The 0.57 offset ratio is essentially a wall-jet. There is no point at which the spray does not appear attached to the wall with the resolution achieved in the video. There is no obvious difference in the core of the 0.57 offset ratio spray and the core of the spray beyond attachment with the 0.83 offset ratio. As mentioned above, the free side of the spray is qualitatively similar to all other offset ratios.

### WETTED WALL

Despite being waxed to be hydrophobic, droplets cling to the wall along its entire periphery. Not all of them are along the centerline of the spray. Pendant droplets are formed at the peripheries of the spray as a result of the large droplets on the outer edges of the spray (those whose trajectories are not qualitatively altered by the wall's existence) impacting the wall. In addition to these pendant droplets, a film is formed near the centerline of the main spray. The camera was placed behind the acrylic wall to observe this film.

A film was formed within the first 50 mm at all conditions tested here, including the largest offset ratio, 1.16, where the spray did not attach to the wall within this distance. The existence of a film upstream of the attachment point may play an important role in wall cooling in a rocket engine. For the 0.83 offset ratio, the film is again existent upstream of the measured attachment point. At an offset ratio of 0.57 the film exists at injector exit within the resolution of the video. Observations of the film behavior and boundary suggest that the film results from water being drawn up or trapped due to the recirculation zone. While pendant drops occasionally roll down the wall forming thin rivulets, there are an insufficient number of these events to create the film.

The film is never very thick—it is not visible in the view where the camera is parallel to the wall, so it cannot be measured. The lack of visibility is a combination of pendant droplets obscuring the view and the resolution of the set-up. The film never accumulates to a large thickness due to the vertical wall orientation and the shear forces imposed by the gas flow. Unfortunately, measurements from the perpendicular (behind the wall) camera are difficult to obtain. The movement of the film's edge allows it to be observed with the naked eye, but discerning the edge from single, still images is challenging. To date, a robust image processing technique has not been implemented. However, the upstream initiation of the film can be roughly determined by eye. For the 1.16 offset ratio, a film has generally been established by 30 mm downstream (exact location dependent on operating conditions). When the wall is at an offset ratio of 0.83, the film is strongly established by approximately 15 mm downstream. As stated above, the inception point for the 0.57 offset ratio is essentially the injector outlet (i.e. the corner between the wall and injector).

### ATTACHMENT POINT

The most certain measurements of attachment length are those made at the 0.83 offset ratio. As anticipated, the reattachment length variation with Reynolds number and momentum flux ratio is small. It should be noted that the uncertainty in reattachment point is larger than the uncertainty in the boundary

Mom Flux ratio	$Re_g$	$x_R$ (mm)	Standard Deviation	$x_R/D$	$x_R/H$
42	$5.9 \times 10^5$	27.1	4.1	1.78	2.15
53	$7.7 \times 10^5$	28.7	1.9	1.88	2.27
80	$7.8 \times 10^5$	28.7	1.6	1.88	2.27
110	$13 \times 10^5$	28.5	1.5	1.87	2.26
87	$12 \times 10^5$	28.0	1.6	1.83	2.22

**Table 2.** The reattachment length is relatively constant despite changes in Reynolds number and

location. The reattachment point uncertainty includes uncertainty in both the location of the boundary and the location of the wall. The ability to differentiate the boundary of the spray from the wall also plays a role as the separation between the two gets down to a few pixels. (As a guide the scale factor is approximate 0.1 mm per pixel; resolution, per se, was not measured.) Considering all of these factors, the variation in attachment point observed at the 0.83 offset ratio is likely within the uncertainty of the measurement.

The average reattachment length, across all operating conditions, at 0.83 offset ratio is 28.2 mm. The standard deviation in reattachment length at a single operating condition is typically in the vicinity of 1.7 mm. However, for the lowest momentum flux ratio operating condition, where the spray boundary exhibits strong instability [9], the standard deviation is much larger, 4.1mm. Even at large momentum flux ratio, the reattachment point is not steady: small variations occur very rapidly. From one frame of the high-speed movie to the next, a time on the order of 0.15 ms, the reattachment point sometimes changes by one or more millimeters. The average reattachment length, operating condition and standard deviation are given in Table 2.

The ratio of attachment length to injector diameter ( $x_R/D$ ) for single-phase, planar jets is reported in the literature as 1.44 [5]<sup>1</sup>. This value is for jets with Reynolds numbers of 20,000. While this value is an order of magnitude lower than the Reynolds numbers in the current studies, similar values could be expected since Reynolds number has little impact on reattachment length above a value large enough to ensure turbulent flow [3, 10]. No single-phase data at conditions nearer the ones in the current study were found for round jets; additionally, no data was found on round jet attachment in the range of offset ratios examined here. The  $x_R/D$  for the spray at 0.83 offset ratio is 1.85 as reported in Table 2. This result is in the neighborhood of the single-phase result, but the two are different enough to be outside of expected uncertainties in the measurements.

The 1.16 offset ratio results support the finding that planar, single-phase results do not predict attachment points for multiphase flows. The spray was imaged up to 90 mm downstream. While the spray is attached to the wall in isolated frames, the majority of the data does not show any attachment. In other words, the attachment point is beyond an  $x/D$  of 5.9. The single-phase literature [5] reports an attachment length of 2.8 at an offset ratio of 1.16.

The existence of a multiphase flow appears to delay the attachment of the jet. Of course, the measurement of when the spray core attaches to the wall is not directly analogous to the measurement of single-phase jet attachment. The spray is a visual measurement of when the main, dark core contacts the liquid; the single-phase measurements from Lund [5] are taken from movement of titanium dioxide on thin oil films, a measure of shear at the wall. The important finding, then, is that using the single-phase, planar jet attachment length will underpredict the length at which the spray core attaches to the wall. This discrepancy between the attachment point of the two-dimensional single-phase and three-dimensional multiphase flows is not unexpected. Attachment length is determined by the development of the lower-pressure zone (recirculation). This zone is, in turn, influenced strongly by boundary conditions and the geometry of the jet. The formation of a film and the lack of the no-slip condition over parts of the recirculation zone would be expected to have some impact on the attachment. Similarly, the finite width of the recirculation zone and the ability to entrain air along the sides of the jet should effect attachment.

From above, it is also clear that the attachment point (single- or multiphase) overpredicts the location where a film begins to be formed. Since the prediction of the attachment point and location of initial film formation may be important when predicting wall-cooling effectiveness, single-phase attachment data should be used with extreme caution.

<sup>1</sup> Note that the  $H/D$  used by Lund differs from that used here. Lund measures  $H$  to the edge of the jet; this paper uses terminology more standard to round jets and measures  $H$  to the jet centerline.

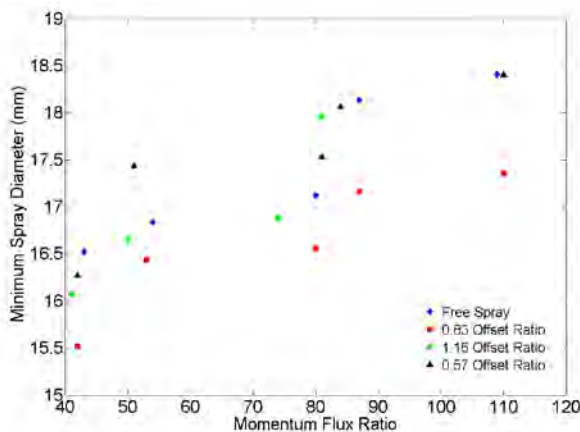


## SPREADING

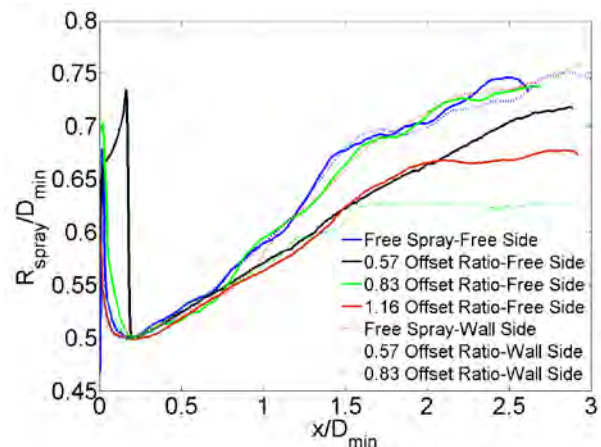
The spreading (or spray angle) of the spray effects not only the attachment point but will also affect the mixing between wall elements and other injectors in a real engine. While the sprays qualitatively appear similar, the presence and distance of the wall does quantitative impact the sprays. The definition and measurement of spray angle is not always clear and consistent and is very sensitive to noise, so here the spreading of the sprays will be compared through comparisons of the averaged spray boundary.

As mentioned in the Experimental Set-Up section, the initial diameter of the spray varies with operating condition, wall location and, to some extent, the lighting conditions. As a result, the boundaries shown here have been normalized by the minimum spray diameter. Due to pendant droplets on the injector surface and resolution, these diameters are not available at the injector exit, but are taken a small distance downstream. This distance varies from test to test; however, as will be illustrated in subsequent figures, there is good overlap between differing conditions and wall locations in the near-injector region of the sprays. From this overlap, it is concluded that the varied locations for determining minimum spray diameter have little impact on the results within the accuracy and resolution achieved by the current set-up. Figure 5 gives the minimum spray diameters for all of the tests considered here. There is a clear spread of about 1 mm between results. The wall distance does not appear to produce a consistent trend, likely due in part to the change in downstream distance of measurement, which is relatively consistent within an offset ratio but changes when the ratio is changed. This downstream distances changes in large part because the injector face is generally not wiped cleaned between changes in momentum flux ratio, but is wiped clean when the wall is moved. The minimum diameter does appear to increase with momentum flux ratio up to a certain point. From 40 to 80, an upward trend at the edge of measurability can be seen, but there appears to be no difference between the diameters at 80 and 110.

The averaged boundaries for all wall spacing are shown for the 80 momentum flux ratio in Fig. 6. Both the free- and wall-side boundaries are plotted as distances from the injector centerline (which is also the initial spray centerline). This momentum flux ratio is shown because it has low noise and some of the largest separation in boundaries; however, the general trends are the same for the other momentum flux ratios examined. Two findings are immediately clear from the figure: there are two families of curves, but these families do not differentiate themselves until between 0.5 and 1 diameter downstream. One family, that with the largest spreading rate, follows the free spray; the other family does not spread as quickly as the free spray. Examining the 0.83 offset ratio, this trend appears to have an obvious cause—the wall impedes the spread of the spray, so that the wall-side of the spray spreads less than the free-side up until the spray contacts the wall (at ~1.5 times the minimum spray diameter). However, an examination of the 1.16 offset ratio results indicates that this simple explanation is not sufficient. For the farther-spaced wall, the boundary with less spread is the one away from the wall, not near it; the boundary near the wall expands as if the wall is not there. (Instantaneous boundaries have been overlaid onto the video to ensure that the labeling of wall- and free-side



**Figure 5.** The minimum spray diameter increases with momentum flux ratio up to a limit.



**Figure 6.** Shown are the boundaries for the 80 momentum flux ratio at all wall offset ratios.

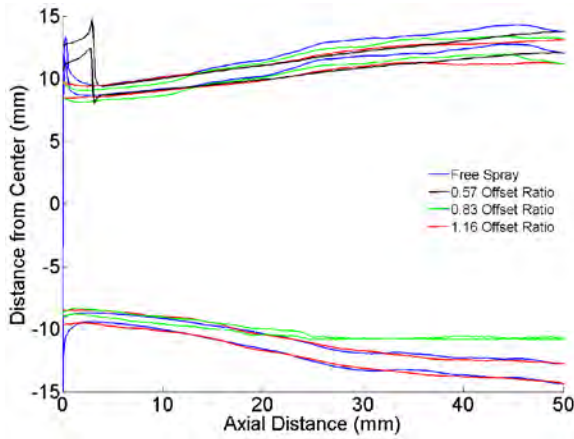
boundary is correct.) The 0.57 offset ratio results, given only for the free-side boundary because the other boundary literally is the wall location, further complicates the picture. This spacing is essentially a wall jet, not an offset jet, and its free-side boundary spread is retarded compared to the free spray. Unexpectedly, though, this spread aligns with the spread of boundaries from the offset jets, at least to wall contact or about two spray diameters downstream. Why the wall-side of a closely-spaced wall and the free-side of a farther-spaced wall should align with that of a wall jet is currently unclear. Likely, complex, three-dimensional vortex and recirculation structures are the cause. In a planar jet, a large recirculation zone effects one side of the boundary uniformly, but in a round jet the recirculation zone must be more localized. Additionally, entrainment in a planar flow is severely hindered on the wall side; here, though, entrainment is less effected as relaxation and fluid movement may occur around the jet. Also at work here, but not investigated yet, is the difference in spread perpendicular to the wall (as imaged and reported) versus the spread parallel to the wall ( $90^\circ$  from those reported here). Davis and Winarto [4] reported that these spreading rates were substantially different with the parallel diffusion being larger. Future work will investigate the spread parallel to the wall as this spread may provide the additional information needed to explain the unexpected results.

What can be drawn from the above results is that the wall does impact the spread of the spray and can impact its spread away from the wall. A few other general conclusions can be drawn as well. The wall-jet (0.57 offset ratio) clearly continues to spread at an approximately constant rate over the entire 50 mm distance investigated. The other boundaries, offset jets and free jets, have a decrease in spreading rate near the end of the frame, generally most evident beyond twice the minimum spray diameter. The change in spreading rate is particularly pronounced for the 1.16 offset ratio free-side boundary after approximately two times the minimum spray diameter. The lesser growth rates continue downstream to the 90 mm distance. Due to the noise in the data and the sensitivity of derivatives, reliable spreading rates are not obtainable, but it can be said, from Fig. 6, that the growth rates in the all conditions falling into the upper family of curves is approximately the same. Growth rates do vary slightly with momentum flux ratio, but the general behavior of two sets of curves, continued growth of the wall-jet and a decrease in growth rate over distance for the other conditions holds. The more prominent decrease in the 1.16 offset ratio free-side boundary also holds.

## STABILITY

The stability of the spray may impact performance by causing time-dependent localized areas of degraded (or enhanced) mixing. Similarly, they may impact the combustion stability of the device either by providing bomb-like localized energy through the aforementioned mixing changes or by coupling with chamber modes. It is possible that the wall could act as a damper for spray variability or it could change the fundamental frequencies associated with an unsteady spray.

The variability (i.e., standard deviation) in boundary location is nearly identical in all instances except the wall-side boundary with the 0.83 offset-ratio wall. In this boundary the variation is substantially reduced prior to the attachment to the wall and essentially zero thereafter. As with the boundary location, the standard deviation increases in the downstream direction. In all but the nearest-wall boundary, the increase continues throughout the 50 mm distance. For the 0.83 offset ratio wall-side boundary, the variation reaches a maximum at a location which roughly corresponds to the location where the two boundaries, wall- and free-side, begin to depart from one another. These findings are illustrated in Fig. 7. The wall has the ability to damp some of the variability of the spray but only in an area very near the wall—in this investigation damping occurs only in the wall-side boundary when the wall is 5 mm from the injector outlet. Even the free-side boundaries of the sprays with 0.57 and 0.83 offset-ratio wall did not exhibit any damping of motion, i.e. decrease in standard deviation. Variations in the centerline (i.e. spray curvature or leaning) are already substantially smaller than those for the boundaries, and the wall location shows no ability to further decrease them. The condition with the most unsteadiness, the lowest momentum flux ratio condition, does not show as much decrease in variability when the wall is close, so the wall is unable to damp the strong global oscillations present in this condition (see Fig. 8). This inability to damp or change these oscillations also suggests that the unsteadiness arises inside the injector and not as a result of vortex breakdown in the sudden expansion at the injector outlet.

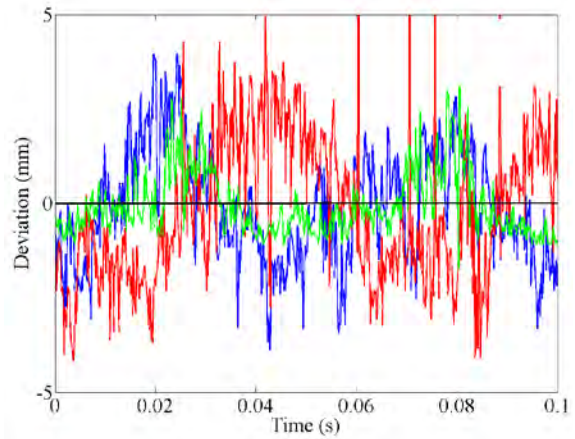


**Figure 7.** The bands over which the spray varies are illustrated for the highest momentum flux ratio. At each measured location (pixel) this graph gives the averaged boundary plus (and minus) the standard deviation at that point. The wall is located towards the bottom of the graph.

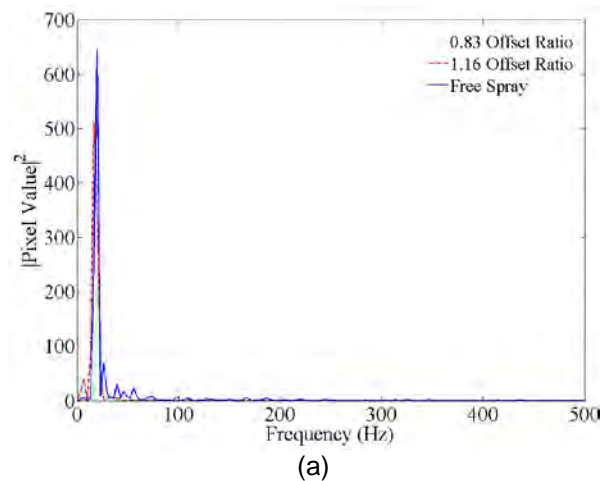
The wall also has some impact on the nature of the variation. When the wall is offset by a ratio of 0.83, more locations on the boundary deviate (from the average) towards the wall than away from the wall. Obviously, then, while more numerous, the departure towards the wall is reduced in magnitude. These findings hold true for both the free- and wall-side boundaries with the 0.83 offset ratio wall. The same behavior is not seen in the 1.16 nor in the 0.57 offset ratio conditions. From these findings, then, it is clear that, while the hypothesis that the wall could act as a damper are technically true, the wall will not act as a damper in practical engine cases. Only the unsteadiness in the edge of the spray very near the wall, if the wall is close enough, is damped.

The above findings that the wall is an ineffective damper hold true for overall variation.

The standard deviation results apply to random, chaotic motions as well as to organized motions. Random motions tend to be more tolerated in many applications whereas organized motions are associated with combustion instabilities. The effect of the wall on organized motions can be more strongly illustrated through examination of the frequencies. In general, the spectral energy of parameters near the wall with a 0.86 offset ratio is lower than those of other parameters. (For example, the overall and peak values shown in Fig. 9 are lower for the 0.86 offset ratio.) The free-side boundary is not affected by the wall as much—its spectral energy is near that of the other geometries. In the case of large-scale periodic movement, as seen in the lowest momentum flux ratio case and illustrated in Fig. 8, the wall does have some damping effect, but even near the wall the strong frequency is still clearly visible. In addition to suppressing some of the organized motion, it may be possible for the wall to alter the dominant frequencies in some cases. While the current type of analysis does not detect changes, a more robust frequency analysis method (using proper orthogonal decomposition) [12] indicated a shift in the dominant frequency of the 1.16 offset ratio case at the momentum flux ratio of 80. The free spray exhibited a lower dominant frequency than the 1.16 offset ratio geometry (6.5 Hz versus 32.7 Hz). However, this shift, is unlikely to be a complete change in behavior since the higher frequency is, within the frequency resolution available, a multiple of the free-spray frequency. Additional details and verification of this result for multiple locations within the spray remain underway, so at this time the reason for this shift is unclear. The result does highlight that the wall effects on the spray are not limited to suppression near the wall and that some of the unsteadiness observed GCSC injectors originates



**Figure 8.** The deviation of the wall-side boundary from the average is shown over 0.1 seconds for the lowest momentum flux ratio.



**Figure 9.** Even for conditions with strong organized motions, such as the lowest momentum flux ratio the wall has little impact on the dynamic behavior.

within the injector body and not as a result of the sudden expansion to the atmosphere. This result supports earlier findings for free sprays [9].

## SUMMARY AND CONCLUSIONS

This work has examined the impact of a parallel wall on a nearby spray formed by a GCSC injector. Emphasis has been placed on characteristics that may impact rocket engines. The placement of a wall near the spray does not alter the spray qualitatively until it attaches to the wall. Away from the wall, after attachment, the spray remains similar to a free spray; at the wall, large droplets are no longer visible after attachment. Quantitatively, however, the wall does impact the spray in some aspects. Within the resolution available here, the wall location (or existence) does not impact the minimum spray diameter; the quantity does increase with increasing momentum flux ratio, however, at least over a range.

The attachment point of the spray is delayed over what is observed in planar, single-phase experiments. However, it should be noted that different methods are used to define attachment between the current spray work and the single-phase literature. The definition here is more relevant to engine cooling. The attachment point is unsteady, especially if the spray exhibits large, unsteady motions. However, attachment is not effected by Reynolds number or momentum flux ratio over the range tested. While the intersection of the wall and main spray core is of importance, a liquid film was also found to exist upstream of this attachment point. The film appears to be formed by the attachment and likely drawn upstream by recirculation. The upstream location the film reaches may be of greater importance than attachment length in engine cooling in situations where droplets have not evaporated prior to attachment.

Despite qualitative similarities, the wall does quantitatively affect the spread, or growth rate, of the spray. Plotting the normalized (by minimum spray diameter) boundaries as a function of downstream distance showed two families of curves. One family follows the free spray while the other has a decreased spread in comparison. All boundaries are essentially the same until about 0.75 the minimum spray diameter downstream. After that, the wall-jet, the wall-side of the 0.83 offset ratio spray and the free-side of the 1.16 offset ratio spray have lower growth rates. It is likely that the complex three-dimensional behavior is the cause of the flip in which boundary is impacted by the wall when the wall is moved; however, the details remain under investigation. The spreading rate parallel to the wall will be examined for clues to the behavior. All of the boundaries, except those for the wall jet (0.57 offset ratio), show a decrease in growth rate downstream of twice the minimum spray diameter. This reduced spread is particularly strong in the free-side of the 1.16 offset ratio spray which has little spread from about twice the minimum spray diameter all the way to 5.5 times the diameter, the farthest downstream investigated.

The wall is able to decrease the spray variability, but not in a way likely to be meaningful to engine designers. Only the boundary very near the wall has a decrease in standard deviation. The spectral energy of the spray also only decreases very near the wall. The wall and a particular offset distance may be useful in varying the dominant frequency in the spray, but this result remains to be verified and appears to only be a whole-multiple change, thus unlikely to strongly alter any stability issues.

Overall, the existence of the wall does not appear to be particularly helpful or harmful to spray behavior. Not surprisingly, its behavior does vary from that of a single-phase jet. The wall can impact mixing, but its offset can be tailored to reduce or eliminate this effect. Also, if droplets exist to the attachment point, a film may be formed which could aid in cooling. However, the film does not appear to be strongly atomized, so it may also adversely impact performance.

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